



Carter, T., Seah, S. A., Long, B. J. O., Drinkwater, B. W., & Subramanian, S. (2013). UltraHaptics: Multi-Point Mid-Air Haptic Feedback for Touch Surfaces. In *UIST '13 Proceedings of the 26th annual ACM symposium on User interface software and technology*. (UIST '13). New York, NY, USA: ACM. 10.1145/2501988.2502018

Link to published version (if available):  
[10.1145/2501988.2502018](https://doi.org/10.1145/2501988.2502018)

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# UltraHaptics: Multi-Point Mid-Air Haptic Feedback for Touch Surfaces

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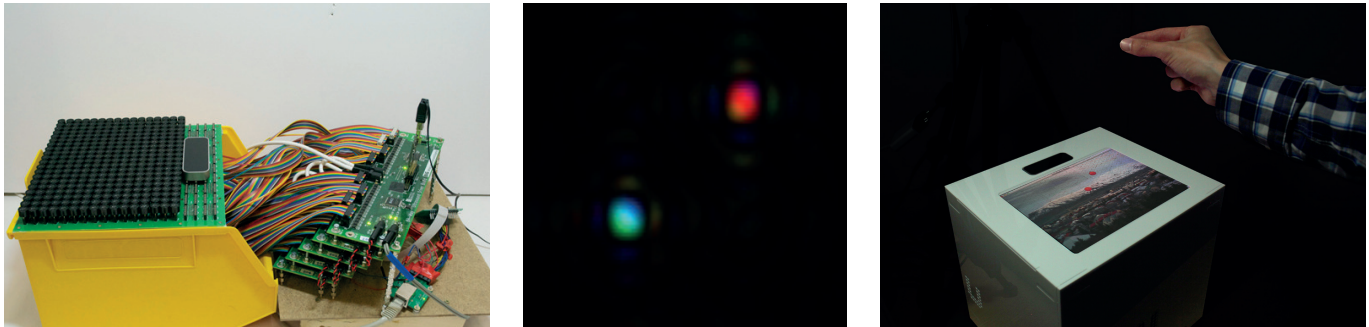


Figure 1: The UltraHaptics system. Left: the hardware. Centre: a simulation of two focal points, with colour representing phase and brightness representing amplitude. Right: receiving two independent points of feedback while performing a pinch gesture.

## ABSTRACT

We introduce *UltraHaptics*, a system designed to provide multi-point haptic feedback above an interactive surface. *UltraHaptics* employs focused ultrasound to project discrete points of haptic feedback through the display and directly on to users' unadorned hands. We investigate the desirable properties of an acoustically transparent display and demonstrate that the system is capable of creating multiple localised points of feedback in mid-air. Through psychophysical experiments we show that feedback points with different tactile properties can be identified at smaller separations. We also show that users are able to distinguish between different vibration frequencies of non-contact points with training. Finally, we explore a number of exciting new interaction possibilities that *UltraHaptics* provides.

## Author Keywords

Haptic feedback; touch screens; interactive tabletops.

## ACM Classification Keywords

H.5.2. Information Interfaces and Presentation: User Interfaces

## INTRODUCTION

Multi-touch surfaces have become common in public settings, with large displays appearing in hotel lobbies, shopping malls and other high foot traffic areas. These systems are able to dynamically change their interface allowing multiple users to interact at the same time and with very little instruction. This ability to 'walk-up and use' removes barriers to interaction and encourages spontaneous use. However, in return for this flexibility we have sacrificed the tactile feedback afforded by physical controls.

Most previous research has focused on recreating this feedback on interactive surfaces. This can be achieved through vibration [2, 4] or by physically changing the shape of the surface [19, 20, 15].

There are situations when receiving haptic feedback before touching the surface would be beneficial. These include when vision of the display is restricted, such as while driving, and when the user doesn't want to touch the device, such as when their hands are dirty. Providing feedback above the surface would also allow for an additional information channel alongside the visual. Previous methods capable of providing this feedback have involved a device worn upon the user's body [33, 30, 32].

In this paper, we introduce *UltraHaptics*, a system that provides haptic feedback above interactive surfaces and requires no contact with either tools, attachments or the surface itself. Instead, haptic sensations are projected through a screen and directly onto the user's hands. It employs the principle of

*acoustic radiation force* whereby a phased array of ultrasonic transducers is used to exert forces on a target in mid-air.

There are three aspects to the creation of the *UltraHaptics* system. First, when augmenting an interactive surface with ultrasonic feedback, it is useful for the array generating the acoustic field to also double as a projected display device. Finding a fitting projection material is not trivial, as it must efficiently permit ultrasound through while also appropriately reflecting incoming light. Through a series of technical evaluations we show that display surfaces with 0.5mm holes sizes and 25% open space reduce the impact on any focusing algorithm while still creating a high performance projection surface.

Second, most existing approaches to generating acoustic fields suffer from secondary maxima that surround the central focus. We need an algorithm that can suppress these secondary maxima while allowing the creation of multiple focal points. We do this by using a concept of control points to define a target for the algorithm by telling it to maximise and minimize the intensity selectively at these control points. Finally, there are no studies on users' ability to discriminate different focal points generated using *acoustic radiation force*. Because focal points do not have well defined edges we cannot rely on the results of discrimination studies done with pins and vibrators. We conduct a series of psychophysical studies to demonstrate feedback points with different tactile properties can be distinguished at smaller separations and that users can identify different tactile properties with training.

We present four main contributions:

1. We outline the principles, design and implementation of an ultrasonic, mid-air haptic feedback system for touch surfaces.
2. We investigate the desirable properties of an acoustically transparent display surface that allows the haptic feedback to be projected through the display from below.
3. We present a series of psychophysical studies that demonstrate feedback points with different tactile properties can be distinguished at smaller separations and that users can identify different tactile properties with training.

## RELATED WORK

Previous research related to *UltraHaptics* can be divided into two categories: alternative haptic feedback methods and previous ultrasonic haptic feedback systems.

### Haptic Feedback Methods

Researchers have explored a wide variety of haptic systems for interactive surfaces. One direction has been to vary the friction coefficient of the surface, either through vibrating the surface with ultrasound [4] or through the use of electrovibration, as demonstrated by TeslaTouch [2]. These approaches are only capable of providing one haptic sensation at a time and apply it across the entire surface. In the case of TeslaTouch, haptic feedback cannot be felt with a stationary point of contact.

Another method is to physically change the shape of the touch surface. FEELEX uses a pin array to deform the surface into a relief image [19]. Alternatively, a fluid layer embedded within the display can be manipulated through the use of electromagnets [20] or pneumatics [15] to alter its shape. These systems require the user's hand to be in direct contact with the surface. In many scenarios, it would be preferable to receive the haptic feedback as the hand approaches the surface.

Separating the visual and haptic displays has been proposed as a solution to this problem. The use of a tool enables users to interact with the system without needing to touch the surface. The haptic pen combines a pressure sensitive stylus with a physical actuator to provide vibrotactile feedback [23]. Similarly, haptic feedback can be provided by a separate static device, such as the SensAble PHANTOM [26] or maglev haptics [3]. However, exploring a virtual environment through a tool creates a disconnect between the user and the content.

Wearable attachments, such as data gloves [33], enable haptic feedback to be provided above the surface while still letting users move their hands freely. SensableRays transfers haptic feedback to an actuator on the user's hand wirelessly through modulated light [30]. Similarly, FingerFlux alters a magnetic field to stimulate the user's finger through an attached magnet [32]. These attachments maintain constant contact with the user's skin and so are always providing some tactile sensation. They also require the user to adorn their hands with the device prior to use, thus limiting the potential for spontaneous interaction.

### Ultrasonic Haptic Feedback

The use of focused ultrasound to stimulate receptors in the human body was investigated as an alternative that requires no physical contact. Research originated in the field of biological sciences in the early 1970s where it was used to diagnose neurological and audiological disorders by analysing changes in perceptual thresholds [9]. By stimulating neuroreceptors within the skin, it has been demonstrated that focused ultrasound is capable of inducing tactile, thermal, tickling, itching and pain sensations [13].

It is important to note that there are two different methods to stimulating receptor structures through ultrasound. The first takes advantage of the *acoustic radiation force*: the force generated when ultrasound is reflected. The ultrasound is focused onto the surface of the skin, where it induces a shear wave in the skin tissue. The displacement caused by the shear wave triggers mechanoreceptors within the skin generating a haptic sensation [11]. The second method bypasses the receptors entirely and directly stimulates the nerve fibres [12]. However, this method requires powerful acoustic fields that penetrate the skin, making it unsuitable for applications designed for prolonged use. We therefore focus on ultrasound incident upon the skin surface.

The use of acoustic radiation force to generate tactile sensations was first demonstrated by Dalecki et al. [5]. A non-focusing ultrasonic transducer submerged in a water bath was used to emit ultrasound onto the finger of a user. To provide

haptic feedback, the radiated ultrasound is modulated down to a frequency detectable by the receptors in the human hand. By moving from using water-based ultrasound to airborne ultrasound the potential range of applications of this technology were broadly increased [18].

The introduction of two-dimensional phased arrays of ultrasound transducers allowed for a dynamic system, with ultrasound focused to a point that can be moved along two axes [17]. While this technique creates a strong focal point, it suffers from the creation of four secondary maxima surrounding the central focus. When the focal point is above the centre of the array, the secondary maxima have about 5% of the intensity of the central focus according to [17], but as the focal point moves further from the centre of the array this value increases considerably. Randomly distributing the transducers across the array rather than arranging them in a grid has been shown to significantly reduce the intensity of secondary maxima [10]. However, this creates an inefficient array in terms of maximising the intensity of the focal points while minimising the footprint of the array.

Previous attempts to create two or more focal points used spatial or temporal multiplexing [1]. The former has the drawback that the secondary maxima of multiple focal points will often constructively interfere with each other creating extra regions of perceivable haptic feedback. Temporal multiplexing on the other hand involves rapidly switching between focal points. This necessarily shortens the duration of ultrasound radiation for each focal point, reducing its intensity accordingly. Both multiplexing methods also risk residual ultrasound from a focal point destructively interfering with other focal points.

When combining ultrasonic haptic feedback with a visual display, various arrangements of transducers have been investigated. They have been positioned in four small arrays along the edges of the display [25], in two columns either side of the display [16] and on the back of the display [1]. Ideally, the direction of the resultant force of the feedback would come from the corresponding visual element. However, these configurations incorporated traditional displays, which are acoustically opaque and so restrict the positioning of the transducers.

## ULTRAHAPTICS

Current systems with integrated interactive surfaces can allow users to walk-up and use them with unadorned hands. Our goal is to integrate haptic feedback into these systems without sacrificing their simplicity and accessibility. To achieve this, we designed a system consisting of an ultrasound transducer array positioned beneath an acoustically transparent display. This arrangement enables the projection of focused ultrasound through the interactive surface and directly onto the users' bare hands. By creating multiple simultaneous feedback points, and giving them individual tactile properties, users can receive localised feedback that corresponds to their actions. The design of our system was guided by two primary requirements: an acoustically transparent display and independent points of feedback.

## Acoustically Transparent Display

With the transducer array positioned behind, the display surface must allow ultrasound to pass through without affecting the focusing and with minimal attenuation. The ideal display would therefore be totally acoustically transparent. Other considerations include being solid to the touch and providing a high quality projected image.

Acoustic metamaterials are materials whose structure is designed to manipulate waves of sound. By artificially creating a lattice structure within a material, it is possible to correct for the refraction that occurs as the wave passes through the material [24]. This enables the creation of a solid material that allows a certain frequency of sound to pass through it. A pane of glass manufactured with this technique would provide the perfect display surface. Furthermore, it has been proven that such a material could enhance the focusing of the ultrasound by acting as an acoustic lens [28].

As such metamaterials are not yet commercially available, we looked to cinema for inspiration. Cinema screens face a similar challenge as speakers are placed behind the screen for optimal synchronisation between the audio and video. They must therefore remain acoustically transparent while providing a high quality picture. Traditionally, perforated screens have been used. Small holes allow the screen to be permeable to sound, but are too small to adversely affect picture quality. Studies show that smaller and closer holes provide better transparency at higher frequencies, although testing was limited to 20kHz [31]. However, the regular patterns of holes can cause moiré and there is a limit to how small the holes can be made. Once this limit had been reached, woven fabric was investigated as a solution [8]. A fine weave creates very small holes and a large percentage of open area, making for an effective cinema screen.

We tested a range of perforated and woven screens with different properties. Details of these tests are presented in the technical evaluation section.

## Independent Feedback Points

In order to relate points of haptic feedback to on-screen elements, users must be able to identify the presence of multiple feedback points. If users are able to distinguish between points with different tactile properties, meaning can then be attached to them. There are both technical and perceptual issues associated with this.

### Technical Issues

Previous studies positioned focal points 50mm apart [1]. At this distance, interface elements would have to be sparsely distributed if they are to provide haptic feedback. Furthermore, the problems associated with both spatial and temporal multiplexing increase as the distance between focal points is reduced, rendering these approaches unworkable. We therefore decided to adapt and extend an alternative focusing method so that each element of the transducer array can contribute to multiple focal points at the same time. This approach was then evaluated by taking measurements of the created acoustic field.

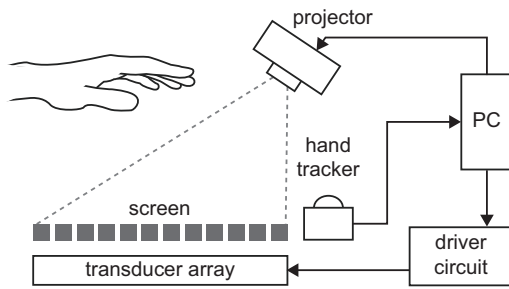


Figure 2: Overview of the UltraHaptics system.

### Perceptual Issues

The human hand is not capable of detecting vibrations at 40kHz. Vibration is detected by mechanoreceptors within the skin. The mechanoreceptors within the skin are responsive to vibrations in the range 0.4Hz to 500Hz [14]. We modulate the emitted ultrasound in order to create vibrations within the optimum frequency range detectable by the human hand. By changing the modulation frequency, we also change the frequency of the vibration on the hand and this can be used to create different tactile properties. Modulating different focal points at different frequencies can give each point of feedback its own independent 'feel' [27]. In this way we are not only able to correlate haptic and visual feedback, but we may also attach meaning to noticeably different textures so that information can be transferred to the user via the haptic feedback.

The minimum distance between points of ultrasonic stimulation at which the human hand can identify them as separate is unknown. It is also unknown whether users are able to distinguish between points at different modulation frequencies. Previous perception studies in haptic stimulation used physical actuators placed on the skin but a non-contact scenario has never been studied. We therefore decided to conduct a series of user studies to establish the limitations of our design.

### IMPLEMENTATION OF ULTRAHAPTICS

In order to evaluate our design we built a prototype system, which is outlined in Figure 2. Challenges in building the UltraHaptics system included constructing the hardware, computing amplitudes and phases for each transducer such that multiple focal points are formed, and modulating simultaneous focal points at different frequencies.

#### Haptic Feedback Loop

Our transducer array has 320 muRata MA40S4S transducers arranged in a 16x20 grid formation. The transducer units are 10mm in diameter and positioned with no gap between them to minimise the array footprint. We chose this type of transducer as they produce a large amount of sound pressure (20 Pascals of pressure at a distance of 30cm), have a wide angle of directivity (60 degrees) and are widely available due to their common use as car parking sensors.

When haptic feedback is required, a phase delay and amplitude is calculated for each transducer to create an acoustic field forming the desired focal points. A lookup table of phase delays and amplitudes is then assembled on the host PC

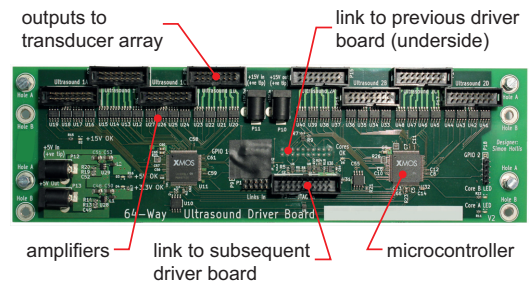


Figure 3: An UltraHaptics driver board.

and sent to the driver circuit via an Ethernet connection. The computation determines the frame rate of the feedback. On a PC with an Intel Core 2 Quad 2.4GHz CPU and an NVIDIA GeForce GTX 480 we achieved speeds of up to 60fps.

The driver circuit consists of a chain of custom-made driver boards (Figure 3). Each driver board features two XMOS L1-128 processors running at 400MHz. They are designed to be stackable, so that a system can be scaled up or down simply by adding or removing driver boards. All connected boards have synchronised clocks driving their outputs at 10MHz. The output signal from the processors to the transducers is a square wave and is amplified from 5V to 15V. Other waveforms could be used but the resonant nature of the transducers mean that a sine wave will always be emitted.

The visual content is projected onto the display surface from above. As users interact with this content, the positions of their hands are tracked by a Leap Motion controller and fed into the application running on a PC. The Leap Motion controller provides the 3D coordinates of the fingertips and palm of the users' hands at up to 200 frames per second. It also provides properties including directional vectors, normals and width of the fingers, which are sufficient to build up an accurate model of the hands. Finally, with 150-degree field of view and eight cubic feet of tracked space, it is very well-suited to detecting input above a touch surface.

#### Computing Phases and Amplitudes

Our algorithm to compute the amplitude and phase for each transducer has been adapted from that proposed by Gavrilov [10]. Rather than a focal point, the approach is able to form 2D focal shapes such as letters of the alphabet. A concept of control points is used to define a target for the algorithm, telling it to maximise the intensity of the ultrasound at these control point positions.

There are three steps to the algorithm [6, 7]. First, the acoustic field generated by a single transducer is calculated to create a large modelled volume. This makes it possible to determine the phase and amplitude at any point within the modelled volume by offsetting the sample transducer for the position, phase and amplitude of each of the transducers in the real array and combining the values.

The control points are then defined upon a 2D plane so that they form the desired shape. Finally, the optimal phases are calculated using a minimum norm solver so that the result-

ing acoustic field is as close to that specified by the control points as possible. There is more than one solution that will create optimal focusing to the control points but some create a higher intensity than others. Solutions are therefore iteratively generated to find the one that creates the highest intensity at the focal shape.

While Gavrilov arranged the control points into a shape, positioning single control points some distance apart creates multiple high intensity points. There is also no reason the control points must lie on a plane. Instead, we can position them to create multiple focal points at different heights. We also extended the control point concept to include null control points. These perform the opposite role to normal control points, instructing the algorithm to generate zero amplitude at that point. By positioning a null control point at each of the positions where unwanted secondary maxima would be expected, we were able to minimise their intensity while optimising the efficiency of the array by having the greatest density of transducers.

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#### Algorithm 1 Our Waveform Algorithm

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```

modelledVolume  $\leftarrow$  integralRayleighSommerfeld()
transducers  $\leftarrow$  transducerArrayLayout(modelledVolume)
loop
  controlPoints  $\leftarrow$  positionControlPoints()
  repeat
    phasesAndAmplitudes  $\leftarrow$ 
      minimumNormSolver(transducers, controlPoints)
  until error  $< \epsilon$ 
  send phasesAndAmplitudes to transducer array
end loop

```

---

#### Modulating Multiple Focal Points

The human hand is not capable of detecting vibrations at 40kHz. We modulate the emitted ultrasound in order to create vibrations that are detectable by the human hand. Modulating multiple focal points at different frequencies is achieved by time multiplexing scenes with different numbers of focal points. For example, in a scenario with two focal points, we must generate four scenes: an empty scene, one with only focal point A, one with only focal point B and one with both focal points. We then move between the scenes as depicted in Figure 4. The amplitude of a single focal point is more than one of a pair of focal points. Therefore, after calculating

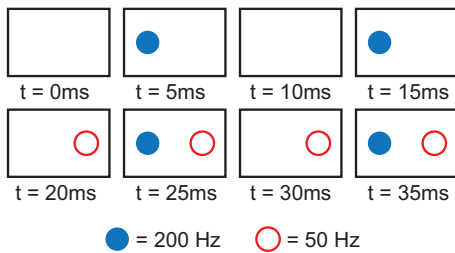


Figure 4: Multiplexing two focal points with different modulation frequencies.

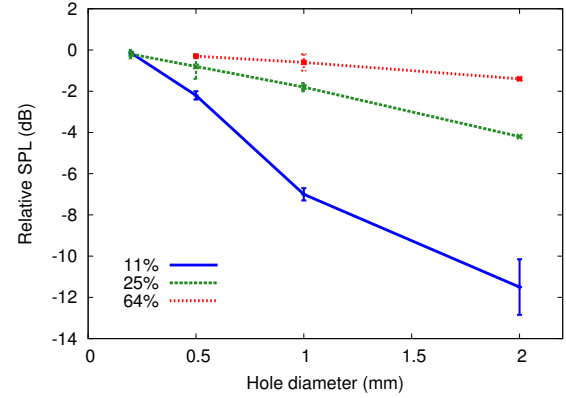


Figure 5: Attenuation of ultrasound through perforated screens with various hole diameters and percentage of open space.

the phases and amplitudes for every scene, we scale the amplitudes of the transducers so that the amplitudes of the focal points remain constant.

#### TECHNICAL EVALUATION

There are three main factors that affect the performance of our system: the acoustic and visual properties of the display surface, the strength of the feedback and the formation of the focal points. In order to evaluate our system, we carried out a technical analysis of each factor. All measurements were made using a calibrated Brüel & Kjær 1/8" pressure-field microphone Type 4138-A-015.

##### Display Surface

We measured the attenuation of the ultrasound as it passed through a selection of perforated sheets and woven fabrics. The display being tested was placed directly on top of a single transducer and the microphone was positioned 20mm above. A digital oscilloscope was used to perform an FFT calculation and extract the 40kHz component in order to isolate the ultrasound from ambient and transient noise. The maximum and minimum values were recorded over a period of 30 seconds and then averaged. The results are presented as a decrease in sound pressure level (relative SPL (dB)) where 0dB is the sound pressure level with no display surface present.

##### Woven Material

We tested the acoustic impedance of two woven fabrics. The first was muslin, a loosely woven cotton fabric. The second was Screen Excellence Enlightor 4K, a finely woven material designed to act as a projector screen for home theatres that feature speakers located behind the screen. The Enlightor 4k is specified as providing uniform attenuation of just -2.5dB between 500Hz and 20kHz. The results are presented in Table 1.

From the poor performance of the Enlightor 4k, we can conclude that the weave does not have enough open space for 40kHz. Conversely, the single layer of muslin performed very well as it has a high percentage of open space. However, this



| Fabric            | Relative SPL (dB) |
|-------------------|-------------------|
| Muslin - 1 layer  | -0.25             |
| Muslin - 2 layers | -0.45             |
| Enlightor 4k      | -3.60             |

Table 1: Attenuation of ultrasound through woven fabrics.

same property causes poor performance as a projection surface, leading to a large loss of visual detail.

#### Perforated Sheet

To further investigate their effect on acoustic transparency, we wanted to control the hole diameter and percentage of open space in the material. We therefore created a set of perforated sheets by laser-cutting small holes into 210 gsm white paper. The results are presented in Figure 5. Both properties have large effects, providing a selection of possible display surface choices that offer minimal attenuation.

#### Focusing Through the Display

Displays that offer minimal attenuation of ultrasound may still affect the focusing of the sound waves due to diffraction and the incident angle of the waves on the underside of the display surface. We therefore took four of the best performing display surfaces and evaluated them on the full size transducer array. The display was placed directly onto the array and the microphone was positioned 200mm above the centre of the array. A single focal point was created at the microphone with no modulation so that a stable measurement could be taken. Again, we extracted the 40kHz component from the FFT calculation to filter out ambient and transient noise. We recorded maximum and minimum values over a duration of 60 seconds. The averaged results are presented in Table 2. All results show a slightly greater attenuation

| Display Surface         | Relative SPL (dB) |
|-------------------------|-------------------|
| 0.2mm at 11% open space | Undetectable      |
| 0.5mm at 25% open space | -2.4              |
| 1mm at 64% open space   | -4.8              |
| Muslin - 1 layer        | -1.2              |

Table 2: Experimental results of the acoustic impedance of display surfaces to focused 40kHz ultrasound.

than the results in Figure 5, which is to be expected due to a higher total SPL from the full array of transducers. It also indicates that the surfaces do have some affect on the focusing of the sound waves. One result of note is that the surface with 0.5mm holes at 25% open space performed better than the one with 1mm holes at 64% open space. This implies that smaller holes reduce the impact on focusing to a greater extent than open space.

#### Formation of Focal Points

Our simulations show that our system creates discrete focal points with low amplitude secondary maxima (Figure 6 far left). To verify our simulations, we scanned the microphone across the horizontal plane at a height of 200mm above the transducer array. A single focal point was created at the same

height above the centre of the array with no modulation. Measurements of the 40kHz component were at 2mm increments. The results of the scan are presented in Figure 6 centre left with amplitude normalised across the measured region.

In order to maximise the amplitude of multiple focal points, a distance that is a multiple of the wavelength should separate them. This allows individual sound waves to contribute constructively to both focal points. Adjacent focal points must also be positioned at least 1cm apart in order for a low amplitude region to be formed between them. Figure 6 shows a simulation of two focal points separated by this minimum distance, while the far right image represents a microphone scan across the same region. The results show that our system is capable of creating distinct focal points at this separation.

Forming two focal points at different heights is also possible. We simulated two focal points being created at heights of 200mm and 400mm from the transducers, with a horizontal distance of 1cm between them. Figure 7 contains simulations of the acoustic field across the horizontal plane at heights of 200mm (left) and 400mm (right). There remains a large gap between the two focal points and the unfocused point at each height has low amplitude compared to the focal point.

#### Strength of Focal Points

The greater the number of simultaneous focal points, the weaker any individual focal point will be. To measure this, we created scenarios with 1 to 5 focal points and measured the pressure generated at one of them. All focal points were created at a height of 200mm above the array surface, were unmodulated and were spaced 40mm apart. A perforated display surface with 0.5mm diameter holes and 25% open space was used. As before, only the 40kHz component was measured. The results are presented in Table 3 as a measurement of the absolute sound pressure level.

| Number of focal points | Absolute SPL (dB) |
|------------------------|-------------------|
| 1                      | 72.6              |
| 2                      | 71.7              |
| 3                      | 68.2              |
| 4                      | 67.4              |
| 5                      | 66.6              |

Table 3: The strength of focal points when different numbers of points are produced simultaneously.

As can be seen from the table, for increasing numbers of focal points the sound pressure level drops slowly with our approach (a doubling in sound pressure level being a difference of approximately 6dB), showing that our method for creating focal points outperforms the theoretical limitations of both spatial and temporal multiplexing.

## USER STUDIES

#### Identifying the number of focal points

We performed a user study to test the design and implementation of our system in forming discernible focal points. We decided to run a focal point discrimination task to determine

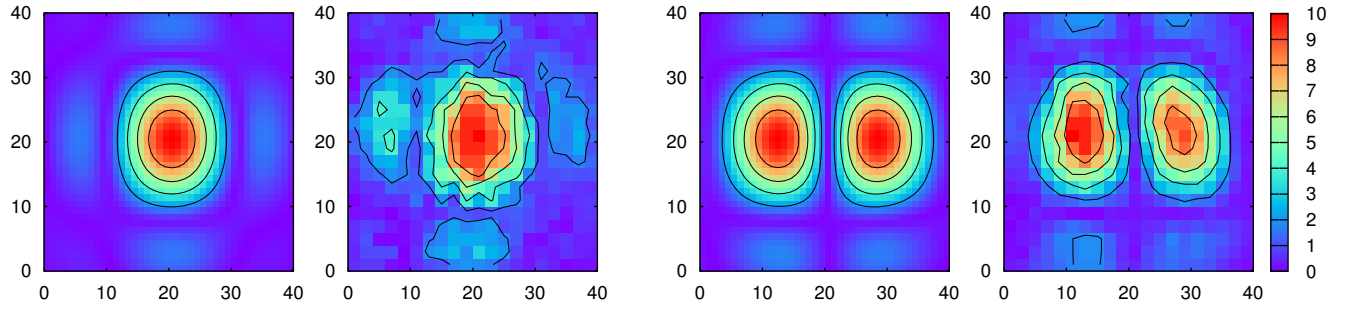


Figure 6: A comparison of the simulated and measured intensities of one and two focal points, each at 200mm from the emitting transducers. Far left: single focal point simulation. Centre left: single focal point measured with a microphone (RMSE 1.30, peak pressure 257 Pascals). Centre right: two focal point simulation. Far right: two focal points measured with a microphone (RMSE 0.77, peak pressure 234 Pascals). All axes are in *mm*.

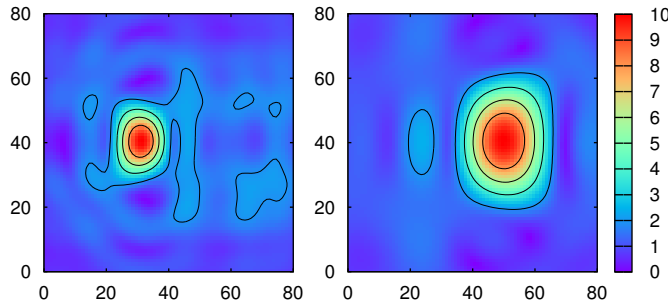


Figure 7: A single simulation containing two focal points placed at different heights. The *xy* position is kept constant, while the left image is taken at a height of 200mm and the right is taken at 400mm. All axes are in *mm*.

whether participants are able to recognise and discriminate between zero, one and two focal point conditions.

In the technical evaluation, we determined that the system is capable of producing two focal points that are 1cm apart. Although the system is able to produce two discrete focal points that are quite close together, this does not mean that the human hand is capable of resolving these points as separate.

As the system uses 40 kHz ultrasound, the focal points generated are about 1cm in diameter (the wavelength of sound at 40 kHz). Previous studies on two-point discrimination tasks, which measures the minimum separation at which two points are felt instead of one, have used static pins that are about 0.5mm wide, which results in a separation threshold of about 2-3 mm [22]. Perez et al. [29] performed two-point vibration discrimination tasks, but also with comparatively small piezoelectric vibrators with a width of 3mm resulting in discrimination thresholds of 2-5mm depending on the frequency of the vibrators. The static pins and vibrators also has the advantage of sharp edges, which helps in the discrimination of two points as it activates mechanoreceptors in the skin that specializes in spatial acuity [21].

We hypothesised that the separation threshold between two focal points would be significantly higher. This is due to the focal points being larger and not having a well-defined edge, which will degrade a two-point discrimination task. However, one of the ways of improving this task with our system would be to modulate the two focal points at different frequencies. Frequency JND (just-noticeable-difference) thresholds have found that the hand is able to discriminate between 12% to 25% difference in frequencies, and the amount of this difference depends on the reference frequency [2]. The hand is able to perceive the differences since vibration thresholds vary with frequency as different mechanoreceptors are activated [14].

#### Participants

A total of 9 participants (3 females and 6 males) aged between 23 and 30 years (mean 27.9, SD 4.1) took part in the study. The experiment lasted for about 60 minutes and consisted of 112 trials. Participants were recruited from within the university.

#### Procedure

We used the system to create either zero, one or two focal points. All the focal points were created at a set height of 200mm above the transducer array. The focal points consisted of modulation frequencies set at 4, 16, 63 or 250 Hz. When there was one focal point, it would be randomly created at locations A, B or C (see Figure 8a) which was set at a distance of either 1 or 2 cm away from the centre of the array. There were 8 conditions of one focal point (two at each frequency).

When there were two focal points, they would be created at locations A and B with a separation of  $d$  cm between the edges of both focal points (see Figure 8b). The factors of each focal point were: *frequencies* - 4, 16, 63, 250 Hz; *location* - A, B. We carried out a full-factorial design resulting a total of 20 frequency pairs. We repeated all 20 pairs for focal point separations ( $d$ ) of 1, 2, 3, 4 and 5 cm giving a total of 100 two-point trials.

We also added 4 trials of the zero focal point condition. All the conditions were presented in a random order to all the participants.



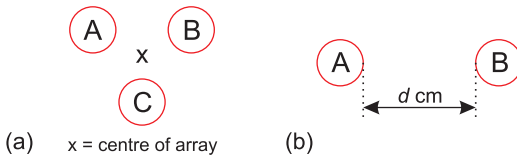


Figure 8: (a) Positions of one focal point condition - A, B or C (b) Separation of  $d$  cm between edges of two focal points.

The system was set-up using the perforated sheet with 0.5 mm diameter and 25% open space as the display surface. There was no visual feedback provided by the system as it was used without any projection on its surface. Three guides were installed by the side of the system at a height of 200mm to help the participants judge the where to put their hands.

All participants went through a 5-minute practise before the experiment started to make sure that they understood the instructions. They were not prompted if they incorrectly judged the number or the type of focal points in one of the trials as we wanted to test the system in a 'walk-up and use' scenario. Following the practice, participants were asked if they had any questions regarding the study, otherwise they proceeded with the experiment. There were five two-minute breaks during the experiment, at every 20th-trial interval, to allow participants to rest their hands.

Participants were asked to only use their dominant hand during the entire experiment. They were instructed to judge the number of focal points of air pressure created by the system. The participants would start each trial by positioning their hand, at the height of the guides, above the ultrasound transducer array. They were then informed to move their hand anywhere along the horizontal plane to find the focal points. If they felt two focal points, they were asked to report if both the focal points felt the same or different. When the focal points felt different, they were asked to report the point they felt was faster and the point they felt was slower. They were allowed a maximum of one minute to explore, however they never exceeded this time. White noise was played throughout the experiment to mask any audio cues to the participants.

### Results

We measured the percentage accuracy that the participants correctly identified the zero, one and two focal point conditions. For the zero focal point conditions, all the participants had an accuracy of 100% (4 out of 4 trials each). For the one focal point conditions, 7 participants had an accuracy of 100% each (8 out of 8) and two participants had an accuracy of 87.5% each (7 out of 8).

Figure 9 shows that participants were able to perceive 2 focal points better if the focal points were of different frequencies. At a separation distance of 3 cm, the mean accuracy of perceiving 2 focal points when the focal points were of different modulation frequencies was 86% (about 10 out of 12) compared to 31% (2.5 out of 8) when the focal points were of the same modulation frequency.

To analyse their ability to discriminate 2 separate focal points, we applied a repeated measures ANOVA with a Greenhouse-

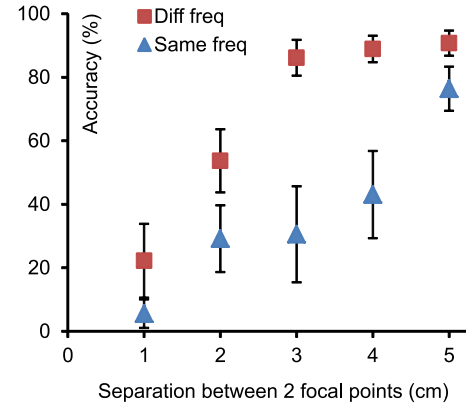


Figure 9: Percentage accuracy of 2-point discrimination when using focal points with the same modulation frequencies and different modulation frequencies (error-bars denote standard error).

Geisser correction on the percentage of correctly identified focal points. We found that there were significant differences in increasing the separation between 2 focal points when both points were of the same modulation frequency ( $F_{(4, 32)} = 15.236$ ,  $p < 0.001$ ) and when both focal points were of different frequencies ( $F_{(4, 32)} = 45.416$ ,  $p < 0.001$ ).

When comparing the results between focal points of the same frequency and focal points of different frequencies, we found that the accuracy of detecting two focal points at separation distances of 2, 3, 4 and 5 cm were significantly higher ( $p \leq 0.041$ ). At 1 cm separation, we found no statistically differences in the results ( $p = 0.071$ ).

It is useful to highlight the differences between this study and that in [1] to avoid the direct comparison of results. The study in [1] consisted of 4 focal points in fixed positions and with constant tactile properties. The participant identified whether each point was on or off and scored out of 4 for each condition. As such, identifying the presence of a single focal point in a condition with two focal points was considered 75% accurate. In our study, the modulation frequency, number and location of the focal points were all varied. Any answer other than the correct number of focal points is considered 0% accurate.

### Identifying the frequency of the focal points

From the first study, we found a trend in the ability to identify focal points as being different for certain frequency pairs at distance of 3, 4 and 5 cm. If participants were able to tell the difference between two focal points which are modulated at different frequencies, then different meanings could be assigned to each point.

We decided to perform a second study to test for the participants ability to identify the frequency of the focal points when there are two focal points.

### Participants

A total of 4 participants (1 female and 3 males) aged between 23 and 30 years (mean 26.8, SD 3.8) took part in the study.

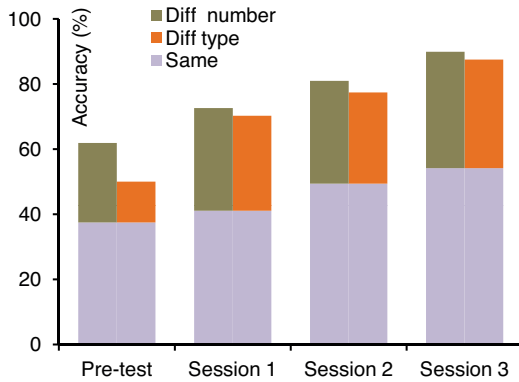


Figure 10: Percentage accuracy of identifying if 2 focal points were of the same frequency (same), were of two different frequencies (diff number) and the type of frequency when there were two different frequencies (diff type).

For each session, the experiment lasted less than 20 minutes and consisted of 42 trials.

#### Procedure

The second study setup was similar to the first study. All the conditions were two focal points created at a set height of 200mm above the transducer array. We chose to test pairs of 4-63, 4-250, 16-250 Hz and their respective mirrored pairs at separation distances of 3, 4 and 5 cm. We also added two same frequency pairs each of 4, 16, 63 and 250 Hz at all three separation distance making a total of 14 frequency pairs per separation distance.

This time, all the participants went through a 10-minute training before the first session of the experiment. The participants were prompted if they answered incorrectly and were told the correct answer to reinforce learning. There was one 2-minute break in the middle of each session to allow participants to rest their hands.

There were a total of 3 sessions. The first session consisted of the 10-minute training followed by the experiment. This was conducted in the afternoon of Day 1. The second and third sessions were both conducted in the morning and afternoon of Day 2, but with no training before the experiment. During the experiment, the participants were informed after each trial if they were correct or incorrect, but were not told the answer.

#### Results

Figure 10 shows that participants got better at identifying focal points and determining the frequency of the focal points with training and time. The overall percentage accuracy for correctly identifying the frequency for each focal point increased from a mean of 50% without any training to 88% in Session 3.

#### DESIGNING APPLICATIONS

Based on the results of our technical evaluations and user studies, we explored the unique interaction possibilities provided by multi-point, above screen haptic feedback. We focused on three areas and created an application for each.

#### Mid-air Gestures

Currently, mid-air gestures suffer from a decoupling of the user's hands from the interface. Users are solely reliant on audio and visual feedback to determine whether their gesture has been successful. Gesture based interactions are therefore often limited to broad, sweeping movements. With our system, individual feedback can be targeted to each finger or hand involved in the gesture, giving the user a greater sense of control and enabling more reserved motions. In Figure 11 left, a two-finger pinch is used to zoom into an image. A focal point is created on each of the thumb and active finger and the difference in modulation frequency between the two grows as they are moved apart.

#### Tactile Information Layers

Tactile feedback has previously been employed to provide a layer of non-visual information to a touch screen. However, receiving this feedback requires covering the visual information. By moving the tactile layer into the air above the display, the user can receive both forms of information at the same time. For example, while browsing a map, population density can be projected as a heat map in the air above (Figure 11 centre).

#### Visually Restricted Displays

There are many scenarios where it is not possible to have visual contact with the display, such as while driving or if the user is visually impaired. In these cases, mid-air haptic feedback can be used to guide the user to the location of an interface element. This is of particular benefit with movable elements, such as sliders, as the user will not be able to learn their position. Figure 11 right, shows the interface for a music player. A strong focal point locates the user's finger above the main controls while a lower intensity point is projected above the volume slider. The user is able to tap on the first focal point to toggle playing or pausing the music and can grab and drag the second point to change the volume.

#### CONCLUSIONS

This paper introduced a new method for providing multi-point, mid-air haptic feedback above a touch surface. Through technical evaluations, we have demonstrated that the system is capable of creating individual points of feedback that are far beyond the perception threshold of the human hand. We have also established the desirable properties of a display surface that is transparent to 40kHz ultrasound. The results of two user studies demonstrate that feedback points with different tactile properties can be distinguished at smaller separations. It was also shown that users are able to identify different tactile properties with training. Finally, we discussed the new interaction possibilities afforded by the *UltraHaptics* system.

#### ACKNOWLEDGEMENTS

This work is supported by the European Research Council (Starting Grant Agreement 278576) under the Seventh Framework Programme and by EPSRC (EP/J004448/1) through its responsive mode funding scheme.

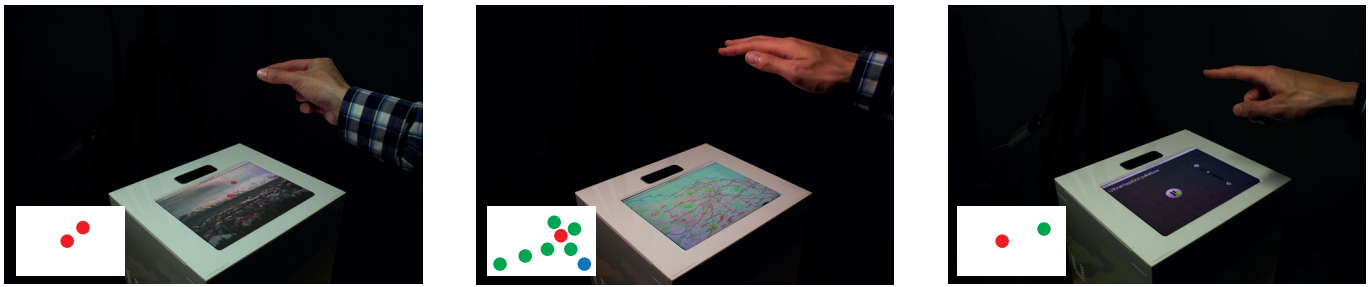


Figure 11: Applications using the UltraHaptics system. Inserts depict focal point locations with different colours representing different tactile properties. Left: a pinch-to-zoom gesture in a photo application. Centre: a tactile information layer conveying population density. Right: a jukebox application with focal points to guide the user to interface elements.

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